VOLUME 81 PAPER No. 806

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

SEPTEMBER, 1955

GROUND WATER PHENOMENA RELATED TO BASIN RECHARGE

by Paul Baumann, M. ASCE

HYDRAULICS DIVISION

{Discussion open until January 1, 1956}

Copyright 1955 by the AMERICAN SOCIETY OF CIVIL ENGINEERS
Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

THIS PAPER

--represents an effort by the Society to deliver technical data direct from the author to the reader with the greatest possible speed. To this end, it has had none of the usual editing required in more formal publication procedures.

Readers are invited to submit discussion applying to current papers. For this paper the final date on which a discussion should reach the Manager of Technical Publications appears on the front cover.

Those who are planning papers or discussions for "Proceedings" will expedite Division and Committee action measurably by first studying "Publication Procedure for Technical Papers" (Proceedings Paper No. 290). For free copies of this Paper—describing style, content, and format—address the Manager, Technical Publications, ASCE.

Reprints from this publication may be made on condition that the full title of paper, name of author, page reference, and date of publication by the Society are given.

The Society is not responsible for any statement made or opinion expressed in its publications.

This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

GROUND WATER PHENOMENA RELATED TO BASIN RECHARGE

Paul Baumann,[1] M. ASCE

SYNOPSIS

In semi-arid parts of the country such as Southern California, water conservation is an enterprise of great importance. The artificial recharge of ground-water basins, which, in Los Angeles County has been practiced for almost 60 years, has proved to be most beneficial as a conservation measure. The Los Angeles County Flood Control District, since June of 1915, has been charged by legislative act with the dual function of flood control and water conservation. During this period and up to January 1, 1955, the District, in cooperation with local agencies, has caused some 1,200,000 acre-feet of potable water to be added to the ground-water supply through both percolation from basins in off-channel spreading grounds and injection through wells. Percolation from basins is normally associated with shallow spreading basins overlying open aquifers and injection through wells with confined, that is, pressure aquifers, primarily attending the control of sea water intrusion.

Ground-water phenomena related to these activities are treated in this paper, in the review and particularly the practical application of previously developed theory.

INTRODUCTION

In the study of ground-water phenomena related to basin recharge, two cases must be treated separately, namely, open and confined aquifers. Common to both cases, however, is the fundamental premise that the flow of water through porous media, such as sand, is laminar; that its velocity is in accordance with the Darcy law; and that the rate of flow is based upon vertical sections, in accordance with the Dupuit theorem, except in special cases as hereafter discussed.

In applying this law and theorem to undisturbed ground-water streams it is found that, in general, the velocities are low and that there is a lack of spectacular features compared to those of surface water hydraulics. The picture changes, however, when the ground-water stream is disturbed, due to such influences as recharge from the surface and the formation of a mound, superposed on the original undisturbed ground-water table. In an open aquifer the mound will necessarily have a free water surface whereas in the case of a confined aquifer, a pressure mound will form. It is these rather fascinating phenoma that this paper is concerned with. For the mathematical background of these phenomena reference is made to previous work by the writer in this

1. Asst. Chf. Engr., Los Angeles County Flood Control Dist., Los Angeles, Calif.

field.[2] Hence, this paper is confined to the discussion of those features which are believed to be of special, practical interest.

Recharge from Spreading Basins

Depending on the shape of the spreading basins the mound will be treated as two- or three-dimensional. Hence, two cases will be considered, namely, the recharge from a strip basin, for example a canal or a stream channel, the width of which is small compared to its length and the recharge from a basin, the shape of which may be approximated by a circle.

If clear water is caused to seep into the ground from a shallow basin it will trickle through the pores, free from hydrostatic pressure, solely under the influence of gravity. The rate of infiltration is governed by the properties of the soil and the viscosity of the water. Because viscosity varies with the temperature the rate of infiltration must vary accordingly. However, in the study of ground-water phenomena related to basin recharge it is permissible to use average values of temperature and to consider them as being constant. Furthermore, idealization of soil properties is necessary through the use of average values of permeability and porosity and of the slope and magnitude of the aquifer, extending over areas of several hundred acres.

Fig. 1 shows a photograph of the District's largest spreading grounds located on the bench lands of the Rio Hondo and comprising 443 acres of area.

I. Strip Basin

a) The Growing Mound

When the trickling seepage reaches the undisturbed ground water table a mound begins to form. This mound is a ridge and may be considered as two-dimensional. At its inception the initial width of this mound will equal the width of the spreading strip. The mound will now grow in height and spread in width. In case of a horizontal initial ground-water table the spreading will be symmetrical relative to the center of the strip basin and unsymmetrical if the initial ground-water table is inclined.

The spread of the mound takes place in form of a wave both upstream and downstream from the spreading strip. This wave will be called the mound wave. The celerity of the wave may exceed by more than ten times the initial velocity of a particle of ground-water. The propagation of this mound wave resembles the mechanics of a tidal wave in an estuary. The rate of propagation decreases with the increase of the wave length, that is to say, the distance from the spreading strip and the initial ground-water depth, and increases with the rate of infiltration.

The rate of growth in height of the mound depends primarily on the rate of infiltration and the distance from the spreading strip to a control. No ground-water movement can continue indefinitely in the absence of a control. The control may be in form of the bank or bed of a stream; of a trench or pit, such as a gravel pit; of a pumping trough; or of the escarpment along a lake or the seashore. In principal, a control is an area of discharge whereby the ground-water levels may be kept constant. The idealized control is a vertical seepage surface extending from top to bottom of the aquifer, thereby terminating it along the respective vertical plane. It is axiomatic that the greater the

2. "Ground Water Movement Controlled Through Spreading" by Paul Baumann, 1952 Transactions, ASCE., Vol. 117, p. 1024.

distance from the spreading strip to the seepage surface, the higher the mound may rise before control by the seepage surface becomes effective. The term control, therefore, pertains primarily to the maximum depth the ground water stream may sustain.

The ultimate height to which a recharge mound may rise above the initial surface of a ground water stream in a given aquifer is therefore governed by the rate and duration of infiltration and the vertical distance between the initial ground water surface and the surface of the ground or the distance between the spreading strip and the control. If the control is governing and the mound reaches its ultimate height without reaching the ground surface, then steady flow will obtain. In this case the native ground-water stream will flow through the stable mound system and will be increased by the recharge flow upon reaching its zone of influence. In the paper referred to the configuration of the stable mound is shown[3] as a solid line. The dash line indicates the straight line approximation of the stable mound. It is evident that for practical purposes the difference between the true and the approximate, straight line configuration is of little consequence.

When the recharge water reaches the undisturbed ground water table and thereby gives rise to the mound so as to create an adverse gradient, the native stream is checked and therefore must go into storage in the pore space above its initial surface. In addition, part of the recharge water will likewise flow into storage in an upstream direction while the balance will flow downstream toward the control and at a rate sufficient to (1) replace the native ground water stream, and (2) maintain the growth of the mound. Hence, the rate of growth of the mound will depend upon the excess of the rate of infiltration per unit width of spreading strip over the corresponding rate of native ground-water flow. The ratio of infiltration rate and the rate of native ground-water flow per unit length of strip is, therefore, an important parameter attending spreading operations. Normally this ratio is great in that native ground-water movements are limited by gradients of, generally less than 0.01, whereas the rate of infiltration is primarily governed by a gradient which approaches unity.

In the light of the foregoing it follows that the growth of a mound, in the absence of compensating extractions of ground-water through pumping or other means, will tend to be rapid and that in course of time and duration of recharge, the mound will reach the surface of the ground and therefore the free water in the spreading basin. A continuous pressure system will then have been created between the spreading basin and the ground-water body. Since this condition is predicated on the mound not reaching stability before reaching the ground surface, it follows that the rate of infiltration must now drop off because of the progressive flattening of the slopes of the mound. If native ground-water flow existed, then the rise of the mound to the surface may have serious consequences due to water-logging of the ground unless prevented from so doing by pumping extractions. This leads to the wisdom of combining spreading with pumping for complete control of the mound phenomenon. It is axiomatic that ground water extracted through pumping must be put to beneficial use. In Los Angeles County close to two-thirds of the total use of water is supplied from ground water. Hence, pumping is performed in all areas where recharge is performed. However, pumping in general lacks proper coordination with recharge. Consequently, the purpose of proper control for the systematic accomplishment of maximum water conservation is not served.

3. Ibid, Fig. 1, p. 1029.

The time requirement for a growing mound for an initial gradient of 0.01 and for a distance of 4 feet between the simulated spreading strip and the control was shown.[4] The dimensions, infiltration rate and soil properties used are based upon model tests[5] which served to verify the mathematical analysis. The width of the spreading strip is neglected. It would be insignificant relative to the mound dimensions which, in this study, were carried far beyond the model dimensions. The spreading strip may therefore be represented by a line and, therefore, infiltration by a line source. Of special interest is the rapid, initial growth of the mound associated with the correspondingly rapid movement of the mound wave in both the upstream and the downstream direction. It is obvious that the flow of recharge water in the upstream direction diminishes with time and approaches zero at the instant the adverse gradient disappears. Subsequent thereto the native ground water flow gradually passes through the mound and, together with the entire recharge flow, moves toward the control. Hence, at the time the mound has reached its ultimate height the entire native and recharge flows are discharged through the control. Theoretically, this time is infinite. However, it may be noted[6] that the time required for the mound to become quasi stable is well within finite limits. For a smaller gradient and greater distance to the control the time requirement would be correspondingly increased. For example, for a gradient of 0.0025 and a distance of 30 feet to the control some 2400 hours, as compared to 10 hours,[6] would be required for the establishment of quasi stability.

The initial slope and depth of the native stream and the distance to the control in combination with the rate of infiltration; the permeability; and the effective porosity; these quantities determine the ultimate height of the mound and effective upstream distance of the backwater. Theoretically, this distance is likewise infinite. Practically, however, the rise of the backwater above the initial ground water surface is of no importance once it is no longer measurable.

In model tests, for maximum potential flow,[7] the "basic parabola" was observed which, under mathematical scrutiny, proves to be an approximation of a parabola. It is apparent that the Dupuit theorem is applicable with fair approximation, except near the spreading basin and near the control. In other words, the use of the tangent of the slope angle instead of the sine, is permissible, so long as a ground-water problem can be treated without the need of a flow net.

The model quantities could readily be applied to a prototype of comparable soil properties, initial slope and linear dimensions N times those of the model. The rate of infiltration which was 0.82 cu.ft. per hour per unit length and the time required for the various stages of the mound would then be N times those of the model. Hence, if the linear dimensions of the prototype should, for example, be 200 times those of the model, thus N = 200, the initial slope 0.0025, the distance to the control 800 feet, the time required for the mound to reach practical stability would be approximately 20,000 hours, or 835 days. The ultimate height would be 50 feet and the distance of measurable backwater 60,000 feet. Should the distance between initial ground-water surface and land surface be less than the ultimate height of the mound, for example, one-half or 25 feet and should therefore be governing, then the time required

4. Ibid p. 1031, Fig. 2.
5. Ibid Part III, p. 1050.
6. Ibid p. 1031, Fig. 2.
7. Ibid p. 1055 to 1060.

for the mound to rise to the surface would be approximately 20 hours, or less than a day. At this time, measurable rise of the backwater would have extended upstream from the spreading strip a distance of some 2000 feet. This clearly brings out the rapid spread of the mound wave even in the upstream direction. In the downstream direction less than four hours would be required for the mound wave to reach the control 800 feet from the spreading strip. Based on these soil properties, the time required for a water particle of the native stream to travel a distance of 800 feet would be 5760 hours, or 240 days. Hence, in this case, the average celerity of the mound wave is over 1400 times that of the velocity of native ground water flow through the pores of the soil. This explains the sudden rise of observation wells, several thousand feet from spreading grounds within much shorter periods of time than that corresponding to the rate of native ground water movement.

b) The Disappearing Mound

When a mound has risen during spreading operations and recharge then is discontinued, the mound will drain itself in course of time.[6] Theoretically, this time is infinite. Practically, effective drainage takes place within a time comparable to that of the growing mound.

Using the same scale factor, N = 200 as before and a prototype specific yield equal to that for the rising mound, the time required to effectively drain the mound 50 feet in height and an initial gradient of 0.0025 would be some 30,000 hours, or 1250 days. It would therefore take approximately one and one-half times as long for the mound to drain as for it to form. This time requirement is, of course, increased with the increase of the distance to the control.

A case of special interest develops if the mound has not reached the control and, therefore, is still in the state of growth at the time spreading is discontinued. In this case the mound will not only fade away but will "float" downstream because of lack of hydraulic support from the control. Hence, the passage of the itinerant as well as fading mound will then be manifested through progressively diminishing rises of the water level in wells along its route.

This clearly brings out the controlling influence of the spreading itself, in that the position of the mound crest will remain fixed so long as infiltration from the surface is maintained.

Drainage hydrographs during the disappearance of the mound[8] show the effect of the initial gradient and therefore of the storage associated therewith.

II. Circular Basin

The foregoing outline applies, in general, also to the circular spreading grounds except that in this case the mound will be three-dimensional. Furthermore, the difference in the shape of the mound between a horizontal and an inclined, initial ground water table and, indeed, in the phenomenon as a whole is much more pronounced.

In case of a horizontal ground-water table, the mound wave radiates from the center of the circle uniformly in all directions. Hence, the directrices are the traces of radial, vertical planes which diverge in the direction of flow.[9] Obviously, for a recharge flow per unit length of circumference of the circular basin, equal to that per unit length of the strip basin, the rate of

8. Ibid Fig. 17, p. 1054.
9. Ibid Part II, p. 1047.

growth of the three-dimensional mound is smaller than for the two-dimensional mound. Thus, it may be said that sustained recharge from circular basins is more efficient than from strip basins, in that the three-dimensional mound in one and the same ground water basin tends to spread more uniformly and over a wider area before rising to the surface. Furthermore, after rising to the surface, the rate of infiltration, the so-called acceptance rate, diminishes less rapidly than for the two-dimensional mound and the danger of water-logging the area adjacent to the circular spreading basin is decidedly more remote. This holds true inspite, or rather because, of the fact that the initial rate of infiltration per unit area of a strip basin is greater than that of a circular spreading basin in that for sustained recharge the rise to the surface is the criterion and not the initial acceptance rate.

If a circular spreading basin is causing its seepage to fall upon an inclined ground water table, the mound phenomenon is far more difficult to analyze. To the writer's knowledge, no exact solution has so far been offered for the general case, that is, for unsteady flow and the wave motion. Only for the ultimate condition, that is, the stable mound have mathematical expressions, based on the streamline theory, been developed.[10] Even for this condition it is necessary to assume the infiltration concentrated in one point, namely, the center of the circle. Obviously, recharge through a well which will be subsequently discussed, comes close to satisfying this premise.

For the steady flow condition the stream lines and equipotential contours may be computed. The formation of a recharge stream, entirely separated from the native ground water stream and confined within vertical interfaces, is particularly significant. It means that aside of some diffusion along the interfaces the two liquids, irrespective of chemical and physical similarity, do not mix. This is because of the difference in potentials, that of the recharge flow being the greater. One conclusion then follows immediately, namely, that the spreading stream must asymptotically approach a width which is equal to the total rate of infiltration divided by the rate per unit width of native ground-water flow. The time required therefor is infinite.

We must, therefore, direct our attention to those features which occur within finite times. This will have to be done with some speculation. It is safe to reason that in its early state this mound would not differ much from the circular mound if the initial slope of the ground-water table were quite small which, indeed, it usually is. Hence, the mound would be slightly egg shaped in plan instead of circular, the point of the "egg" facing downstream. Now, with continued spreading, the mound would be growing in all directions but most rapidly in a downstream direction and least rapidly in an upstream direction. Since the streamline theory predicts a point of stagnation at the ultimate upstream boundary of the recharge flow it follows that the mound must approach this point by decelerating its upstream growth. On the other hand the ultimate condition in the downstream direction is the above-mentioned width of the spreading stream. This calls for the progressive elongation of the mound in the downstream direction. Intermediate stages of the mound, though defying exact analysis, may be evaluated for practical purposes by graphical methods. One condition must always obtain for any particular time: the water content of the mound must be equal to the volume of water infiltrated.

Fig. 2 shows the approximate shape in plan of the mound for three early stages in relation to the ultimate shape of the mound.

10. Ibid p. 1049.

Effect of Spreading Mounds on Channel Mounds

A problem that often arises when spreading grounds are located on the bench land next to stream channels is as follows: Under what condition can the recharge water move across the stream channel if a mound has previously formed under the channel and has risen to its surface. In other words, under what condition can the channel mound block the flow from the spreading mound?

Based on the foregoing discussion it follows that to stop the flow from the spreading basin, the water surface of the channel mound would have to rise to the same elevation as that in the spreading basin. If the spreading basin is properly located this could only occur during flood stage at which time recharge operations are not performed because of the turbidity of flood waters. On the other hand, the difference in elevation between the stream channel and the spreading basin must be such as to avoid significant return flow from the spreading basin to the channel. This feature will be further discussed in its proper place.

Fig. 3-a shows a section normal to a stream channel and adjacent spreading ground after the channel mound had risen to the surface and had become quasi stable prior to spreading. The flow net of the channel mound is indicated. Actually, the flow trajectories are curved because of the sloping stream channel and aquifer but the flow net resembles that shown in Fig. 3-a if developed into a plane. Obviously, the curvature of the flow trajectories facilitates the get-away of the flow from the channel mound.

If recharge now commences, a mound will form on the slope of the channel mound, precisely as previously described, in that the flow from the channel mound will play the part of the native ground water stream. The recharge mound will rise rapidly and will, presently, reach the potential of the channel mound. At this time flow from the channel mound toward the recharge mound will cease. This will have the same effect as if the stream bed had been widened so as to extend to the full width of the spreading ground. Hence, at this instant, the total, infiltrated flow from the channel and the spreading ground will be split relative to the centerline of the combined width. Part of the recharge flow will therefore begin to move across the stream channel, together with all of the infiltrated flow therefrom.

As the spreading mound continues to rise an increasing portion of its flow will move across the channel. This condition as shown in Fig. 3-b is likely to be accompanied by a return flow to the stream channel if the spreading basin is merely separated from it by a levee. The flow net shown in Fig. 3-b is likewise developed from a curved surface. The curved trajectories will again facilitate the getaway of flow from both mounds. Only by taking its three dimensions into consideration is it possible to fully understand this flow condition. The actual portion of the recharge water crossing the stream channel for any given condition follows from a balanced flow net.

In assuming the impervious stratum to be horizontal and therefore the flow trajectories to be linear and at right angles to the stream channel a relation between the average acceptance rate q per unit of wetted area and the parameter D/W (see Fig. 3-a) was developed, namely:

$$q = K\left(1 - e^{-\frac{D}{2W}}\right) \qquad (1)$$

in which K = permeability coefficient
and e = base of natural logarithms.

Eq. 1 was arrived at by computing the flow per unit length of channel for flow nets of constant depth D and variable width W. Obviously, the average acceptance rate per unit of wetted area decreases with the increase in width of the channel relative to a constant depth of the aquifer. However, the total acceptance rate Q increases with W although at a decreasing rate.

For example, the total acceptance rate even for D/W = 1 and the stream channel only, Q_1 = 0.387 KW, whereas for a combined width equal to 4 W of stream channel and spreading ground the total acceptance rate Q_2 = 0.468 KW. Obviously, this relation between a given depth of aquifer and the width of the spreading area is of economic importance.

From Fig. 3-b it is apparent that no significant return flow from the spreading basin to the stream channel will materialize so long as the gradient between the two is moderate, namely, not steeper than 5 horizontal to one vertical. This condition is satisfied if the difference in water surface elevation between the spreading basin and the stream channel does not exceed ten feet and the two are separated by the usual broad crested, flat sloped levee.

III. Recharge Through Wells

In connection with ground water basins along the coast and inland bays of California, the recharge through wells is almost invariably connected with the recharge of a pressure aquifer, confined between an impervious stratum at the bottom and at the top. In view of the cost of such an operation per unit volume of water injected as compared to that of basin spreading it follows that recharge through wells will normally only be resorted to where spreading cannot be used.

A recent survey by the California State Division of Water Resources revealed the fact that of a total of 79 such ground-water basins 19 have been contaminated to a more or less critical extent through intrusion of sea water, and that the remaining basins are potentially subject to contamination.

In Southern California the West Coast Basin of Los Angeles County is one of the most critically affected. Here it is a water-bearing zone of inestimable value, the so-called Silverado Zone, which has been causing increasingly grave concern during the past few years. Many water producing wells in the basin area had to be abandoned because of increasing salinity beyond the potable limits. The City of Manhattan Beach alone had to abandon eight of its major wells. In 1950, one of these abandoned wells was made available to the Los Angeles County Flood Control District to conduct a recharge test. The test which extended over a period of some six months proved successful in that it was possible to inject fresh water at reasonably uniform rates and to create a pressure mound.[11] On the strength of the promising test results, the California State Legislature, in its regular session in 1951, approved an appropriation of $750,000 for conducting a large scale recharge test in the Manhattan Beach area. Under contract with the State Water Resources Board, with the Division of Water Resources as its engineering agent, the Flood Control District, in February 1953, embarked on this large-scale test which is still in progress. Although the appropriated State funds became exhausted in November of 1953, the Flood Control District, together with the West Basin Water Association, managed to continue the test on a somewhat reduced scope.

In facing the problem of stemming sea water intrusion into a ground-water basin by means of a fresh water barrier, a principle, not heretofore discussed

11. "Experiment with Fresh Water Barrier to Stem Sea Water Intrusion" by Paul Baumann, Journal, Am. Water Works Assoc. May 1953.

in this paper, pertaining to the difference in specific gravity between fresh water and sea water, must be considered. It is known as the Ghyben-Herzberg principle.[12] In brief, it establishes the fact that in order to balance the pressure of sea water by fresh water at any depth below sea level, a differential head of fresh water between two and one-half and three per cent of the depth in question must be provided. The exact percentage depends, of course, on the actual, relative density of sea water and fresh water at a particular location. At Manhattan Beach a differential head of two and one-half per cent of the maximum depth must be present. But this differential head can only exist so long as the fresh water gradient is seaward which, unfortunately has not been the case under natural conditions in this and other ground-water basins along the ocean front of California. Hence, it is necessary to raise the water table artificially by means of a pressure mound created through the injection of fresh water into the aquifer through wells. Replenishment of the basin will be an important incidental achievement.

In connection with circular spreading basins and inclined ground water table it was pointed out that the two liquids, namely, the native ground water and the infiltrated fresh water do not mix appreciably, so long as the latter has a higher potential. This is likewise true if one of the liquids, such as sea water, has a higher specific gravity than the other and thereby possesses the potentialities of a density current.

Therefore, sea water will intrude a ground-water basin lying below mean sea level in form of a wedge which will creep along the bottom of the aquifer at ever increasing magnitude and will eventually displace the fresh water throughout its section unless repelled by recharge operations. Such pressure produced by means of fresh water injection through wells must satisfy at all points the above minimum requirement. Thus, the spacing of the recharge wells is an important hydraulic parameter besides being of decided economic significance. Basically, the mechanics of the pressure mound thus formed and of the free mound below a circular spreading ground are the same, except with the pressure mound no significant change in storage is involved. Hence, recharge of a confined aquifer lends itself to simplified analysis. The maximum spacing of the recharge wells is determined by the ratio of injection rate and rate of native ground-water flow per unit length of barrier.

Fig. 4 shows a map of the West Coast Basin and the ground-water contours of the confined aquifer prior to the recharge test. The location of the test front in relation to the possible, ultimate recharge line, is indicated, together with the sites of tests on the Manhattan Beach well and on spreading plots conducted simultaneously. Areas "A" and "B" represent quasi unconfined aquifer conditions. The depletion of the basin is evidenced through the deep depressions and the landward gradient as a result thereof. Generally, the basin is confined between the ocean front and the Newport-Inglewood fault.

Recent sand dunes in the test reach, some 90 feet in thickness, are underlain at or near sea level by approximately 20 to 30 feet of relatively impervious Upper Pleistocene sediments which cap the affected major regional aquifer, known as the "Merged Silverado." This confined non-homogenous aquifer, consisting of approximately 100 feet of continental and shallow marine Upper and Lower Pleistocene deposits, bifurcates and appreciably thickens inland and is in hydraulic continuity with several important prolific West Coast Basin water bearing members. Among these are the quasi open aquifers in the areas marked "A" and "B" in Fig. 4.

12. Ibid p. 1061.

As at the test site, the effective bottom of the aquifer is roughly 110 feet below mean sea level it follows that in line with the Ghyben-Herzberg principle, the minimum differential fresh water head required to balance sea water pressure at that depth is 2.75 feet. The test front, 4000 feet in length, parallel to and some 2000 feet landward from the sea shore is formed by nine-12 inch diameter recharge wells, 500 feet apart. Thirty-six 8 inch, four 4 inch, and eighteen 2 inch wells were provided for observation of pressure levels and for sampling. Fresh water is supplied through a pipeline which connects to the West Coast Basin supply line of the Metropolitan Water District (MWD) of Southern California. The arrangement is shown in Fig. 5. Marked thereon also are adjacent, abandoned and producing wells and iso-chlors prior to recharge.

Certain apprehension had made itself felt in regard to the possible, detrimental effect of the "saline wave." This wave was conceived of as the result of displacing that part of the saline water by injected fresh water which had extended landward beyond the well front. Actually, the test proved that this apprehension was quite unfounded; that the sea water intrusion itself is the damaging feature and not the saline wave caused by injection; and that once the intrusion is stopped, the effect of the saline wave is not important. This statement is, of course, predicated on the assumption that the saline intrusion had displaced the native ground-water for a relatively small distance landward from the well front and that, therefore, the volume of saline water landward from the injection wells would be small as compared to that of the native ground water. In general, it was found that the saline wave flattens as it moves landward and that the contaminating effect diminishes approximately with the square of the distance from the recharge wells, if the rate of fresh water injection is such as to maintain the minimum differential head of 2.75 feet at the internodal point between the wells.

Fig. 6-a shows, in a section through the center of the test front, the extent of sea water intrusion prior to commencement of injection. Horizontal and vertical distances may be estimated from the distance between the recharge well and the seashore which is roughly 2000 feet and from the depth below sea level of the aquifer which is approximately 110 feet. The saline water indicated by the cross-hatched area had displaced nearly all of the native water between the ocean and the test front and from there had crept landward in form of a wedge some 3500 feet. The position of the interface between saline water and fresh water was, where conditions permitted, determined through conductivity measurements.

Fig. 6-b shows the aquifer conditions after fresh water had been injected for eighteen months. The injected fresh water is contained within the dot covered bulb. The recharge water had displaced the saline water in form of a crater and had caused it to "slough" off landward and to retreat seaward. The rate of displacement of the saline water naturally depends on the rate of injection which, in turn depends on the injection head relative to mean sea level. The injected water, therefore, has a higher potential than both the sea water and native fresh water and unless agitated does not mix with either of them except through diffusion along the interfaces as previously discussed. Hence, the water volume of the recharge bulb must at all times be equal to the volume of water injected.

The sloughing landward and flattening off of the saline water displaced from the crater is apparent and with it the decreasing contaminating effect of the saline wave.

Finally, Fig. 6-c shows, perhaps with the aid of a crystal ball, the ultimate result of recharge, that is to say, the condition at a time when the recharge operations would have accomplished their objectives. At this time the saline wedge would have been forced seaward far enough for recharge water to escape to the sea. The configuration of the saline wedge would then be that of an inverted, basic parabola. The landward saline wedge would have been reduced to a harmless thin layer along the bottom of the aquifer. In actuality the remaining sea water would have been trapped in depressions along the bottom of the aquifer, or would have been depleted without harmful effect, through pump extractions. The condition as shown in Fig. 6-c would probably establish itself after at least ten years of continuous fresh water injection. Recharge would have to be resumed when the saline wedge had again advanced landward a critical distance. Also, recharge might be maintained at a rate sufficient to prevent re-invasion.

Fig. 7 shows a typical manifestation of the saline wave in terms of chloride ion concentration as it passed observation wells 240, 520, and 1180 feet respectively, landward from the injection wells.

Fig. 8 shows the iso-chlors after 16 months of recharge in relation to the well front. It is interesting to note articulation of the mounds at the recharge wells. Also the merging of these mounds landward from the recharge wells.

Fig. 9 shows the pressure mound configuration at various times along the cross-section normal to the test front, and Fig. 10 shows the mound in profile. It is evident that the pressure mound extends well beyond the terminal recharge wells. Unfortunately the one at the north end had to be shut down and injection discontinued after only a few days of operation because of failure of the clay cap at this location. Hence, the barrier as shown in Fig. 10 was created by only eight recharge wells.

Information Gained Through Experience

The barrier test has clearly demonstrated the superiority of gravel jacketed relative to simple casing wells. Two of the nine recharge wells are gravel jacketed. They have performed satisfactorily throughout the test. Of the remaining seven simple casing wells, one failed immediately after it was put in operation as previously stated, and the others developed weaknesses at various times making shut-down and costly repairs necessary. The main advantage of the gravel jacketed wells rests with the uniform distribution of perforations and the resulting freedom in the movement of recharge water through the gravel jacket into the aquifer. This requires considerably less head than with a simple casing well for one and the same rate of recharge. Hence, the danger of "blow-out" along the contact between well casing and clay cap is correspondingly lessened.

By sterilizing the injected water with approximately eight parts per million of chlorine it was possible to sustain a minimum total injection rate of 4.50 c.f.s. at moderate head. Chlorination, or a similar method of sterilization, is believed essential in connection with well recharge to prevent clogging of the pores by otherwise harmless micro organisms, which are prevalent to some extent in all sources of water and are stimulated to great activity through unavoidable aeration of the recharge water.

Sterilization of clear water diverted from streams, attending large scale recharge operations in spreading grounds, has not been found to be essential.

ACKNOWLEDGMENT

The writer is indebted to H. E. Hedger, M. ASCE Chief Engineer, Los Angeles County Flood Control District, for encouraging and reviewing the paper; to Finley B. Laverty, M. ASCE in charge of the District's Hydraulic Division and his staff of Research and Ground Water Sections, in assisting in the computations and the preparation of exhibits; to Hazel M. Robertson for the typing and assembling of the paper; and, last but not least, to the publications committee of the Society's Hydraulics Division for painstaking review as well as constructive, helpful and fair suggestions.

Fig. 1. Spreading Grounds on Bench Land of Rio Hondo Central Coastal Basin, Los Angeles County.

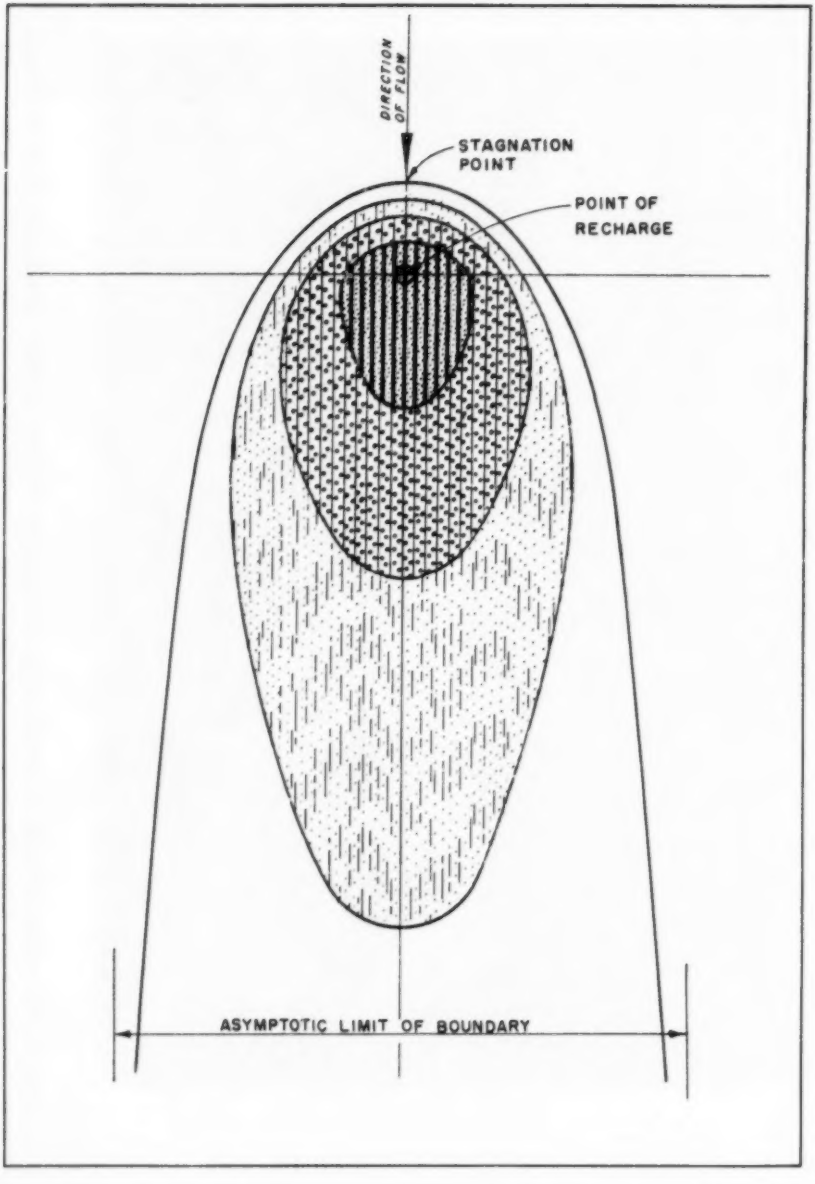

Fig. 2. Growth of Recharge Bulb in Sloping Ground Water Basin.

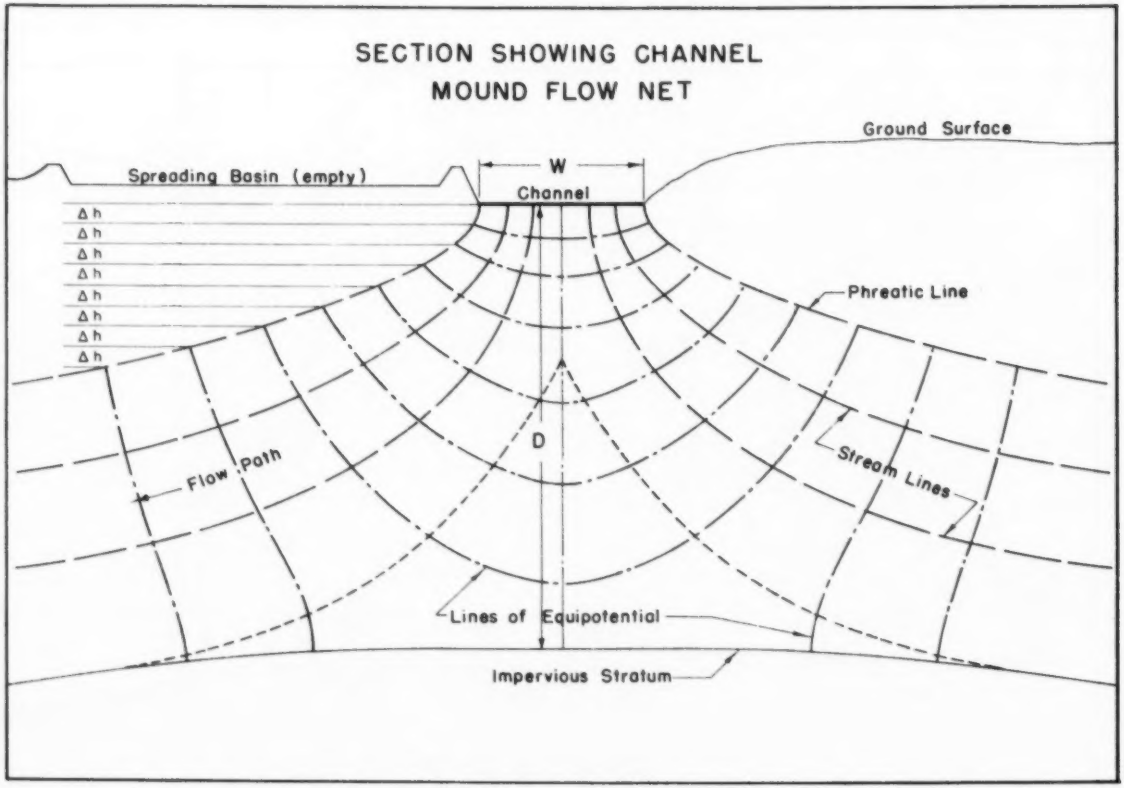

Fig. 3a. Flow Net for Mound under Stream Channel.

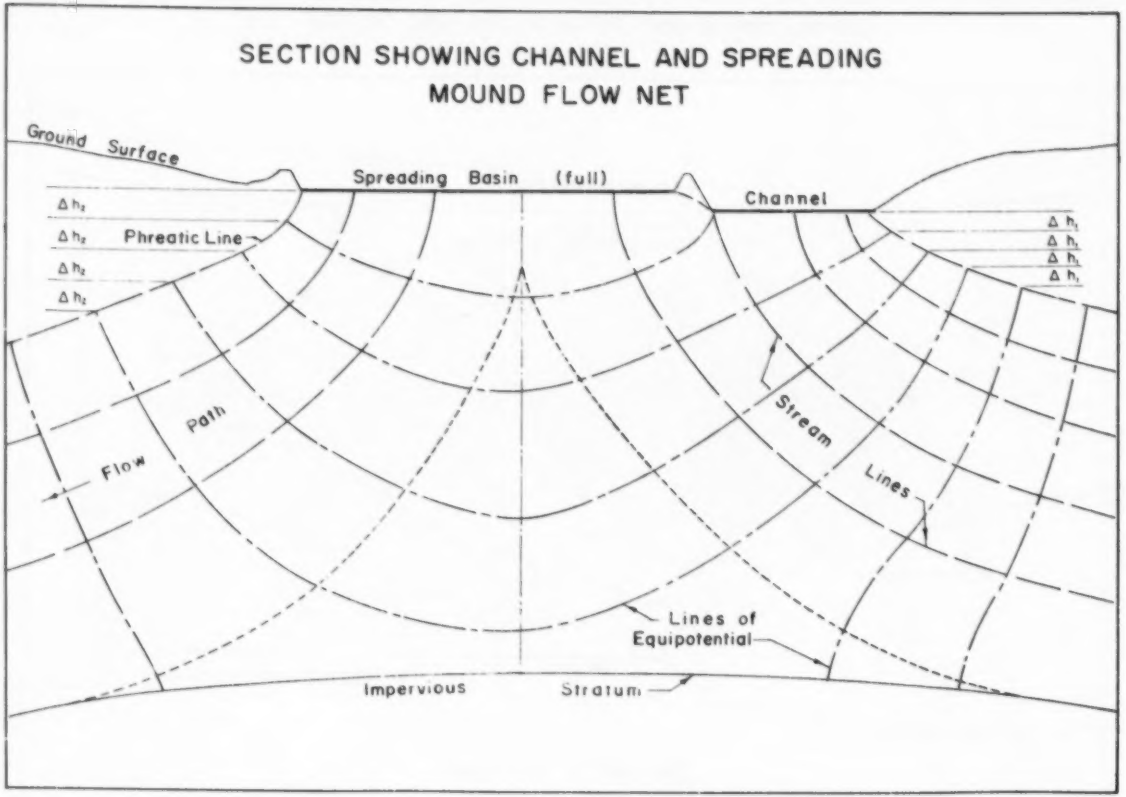

Fig. 3b. Effect of Recharge Mound on Channel Mound.

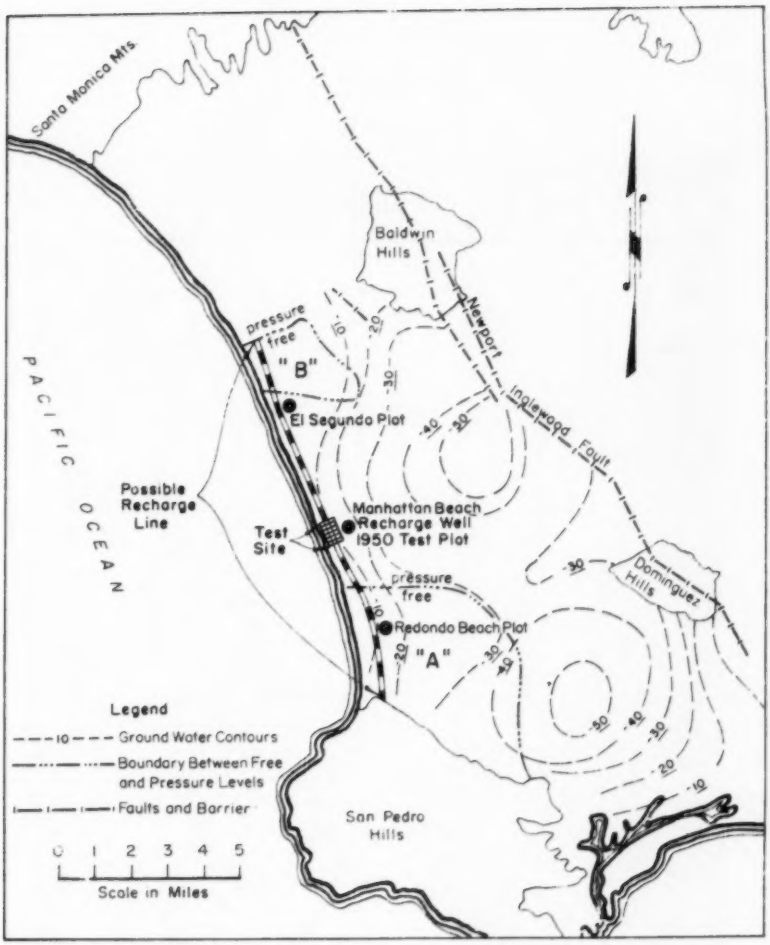

Fig. 4. Map of West Coast Basin, Los Angeles County, showing Test Sites, Barrier Location and Ground Water Contours.

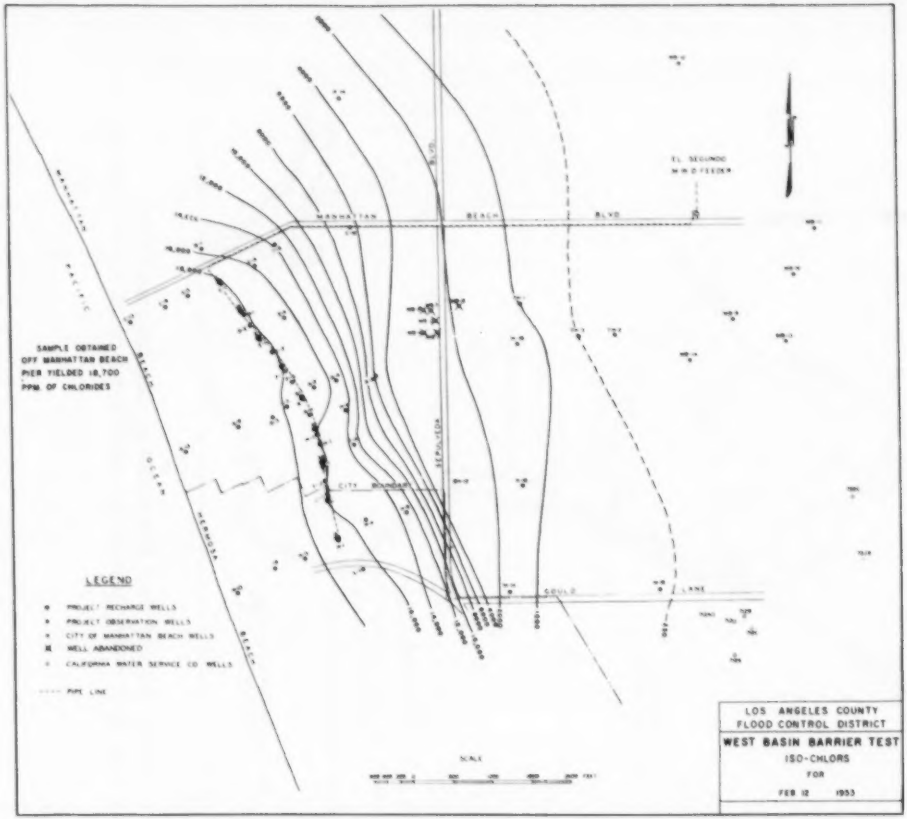

Fig. 5. Plan of Barrier Test Arrangement showing Iso-Chlor Lines prior to Recharge.

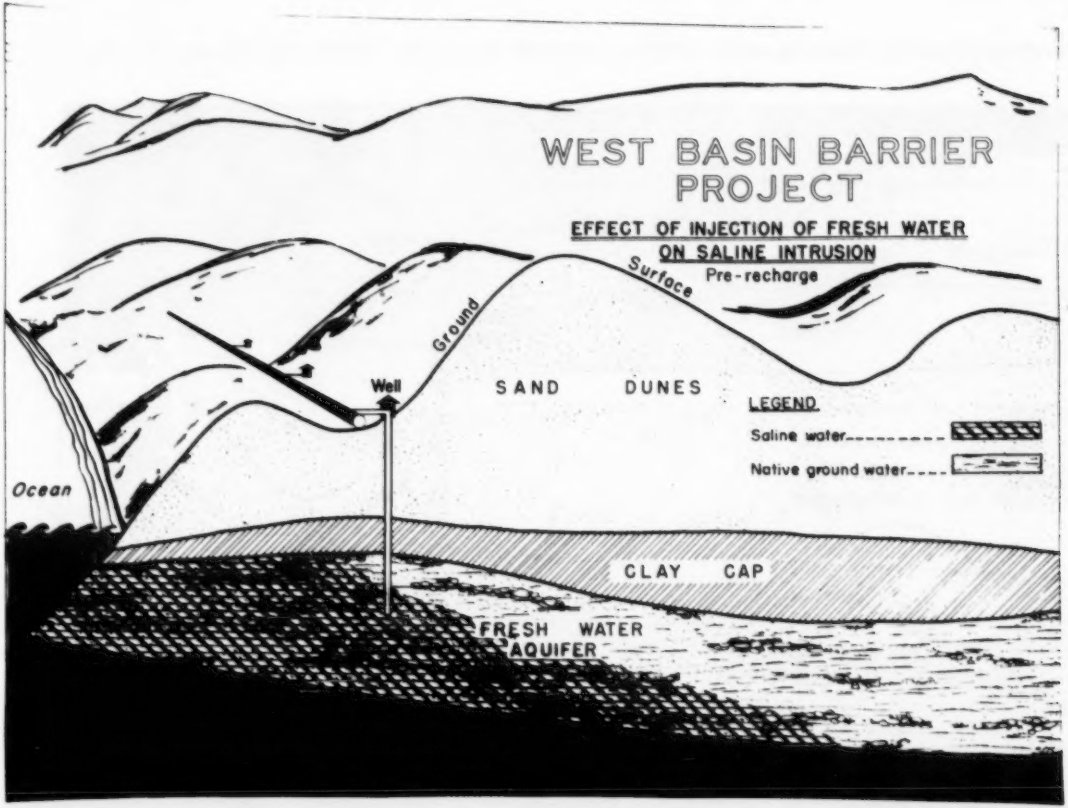

Fig. 6a. Section Normal to Test Front showing Sea Water Intrusion prior to Recharge.

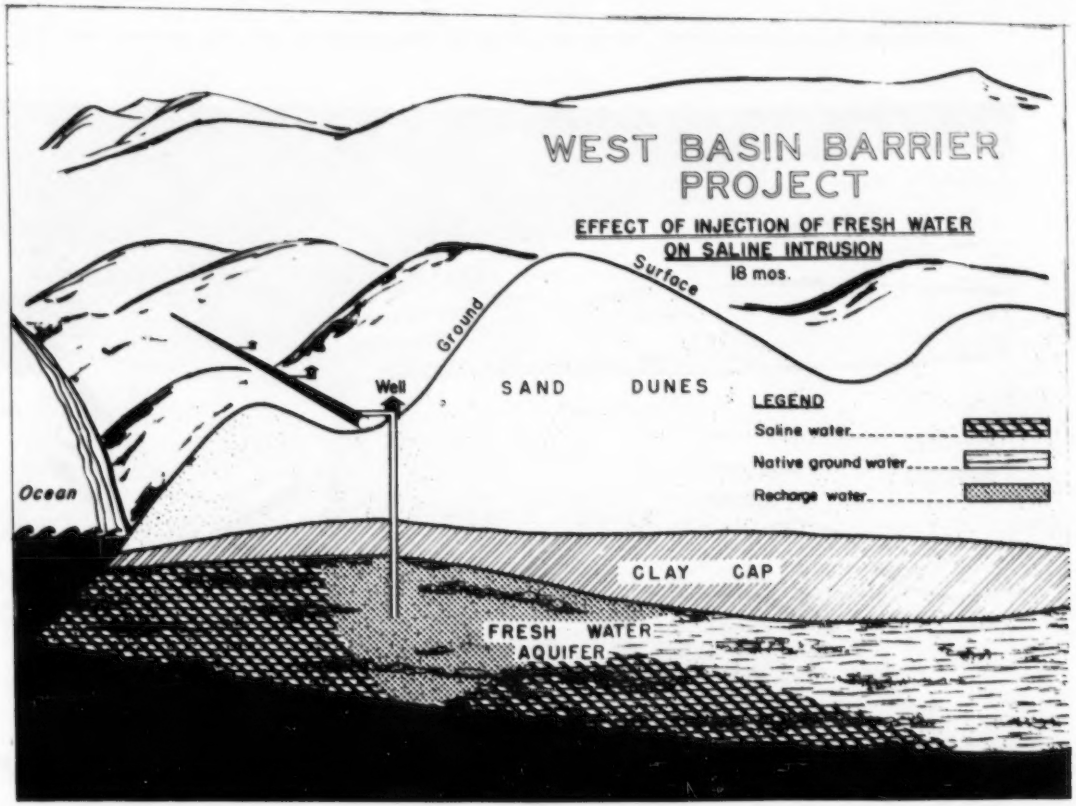

Fig. 6b. Section Normal to Test Front showing Condition After Eighteen Months of Recharge.

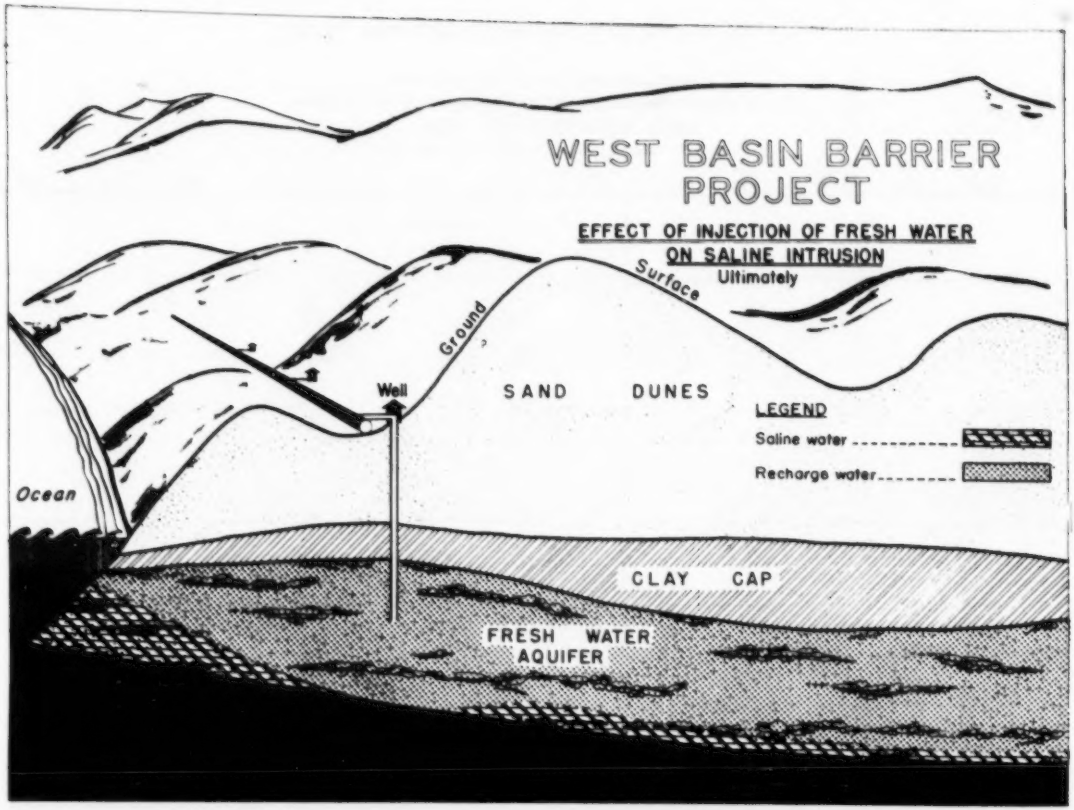

Fig. 6c. Section Normal to Test Front showing Estimated Ultimate Condition.

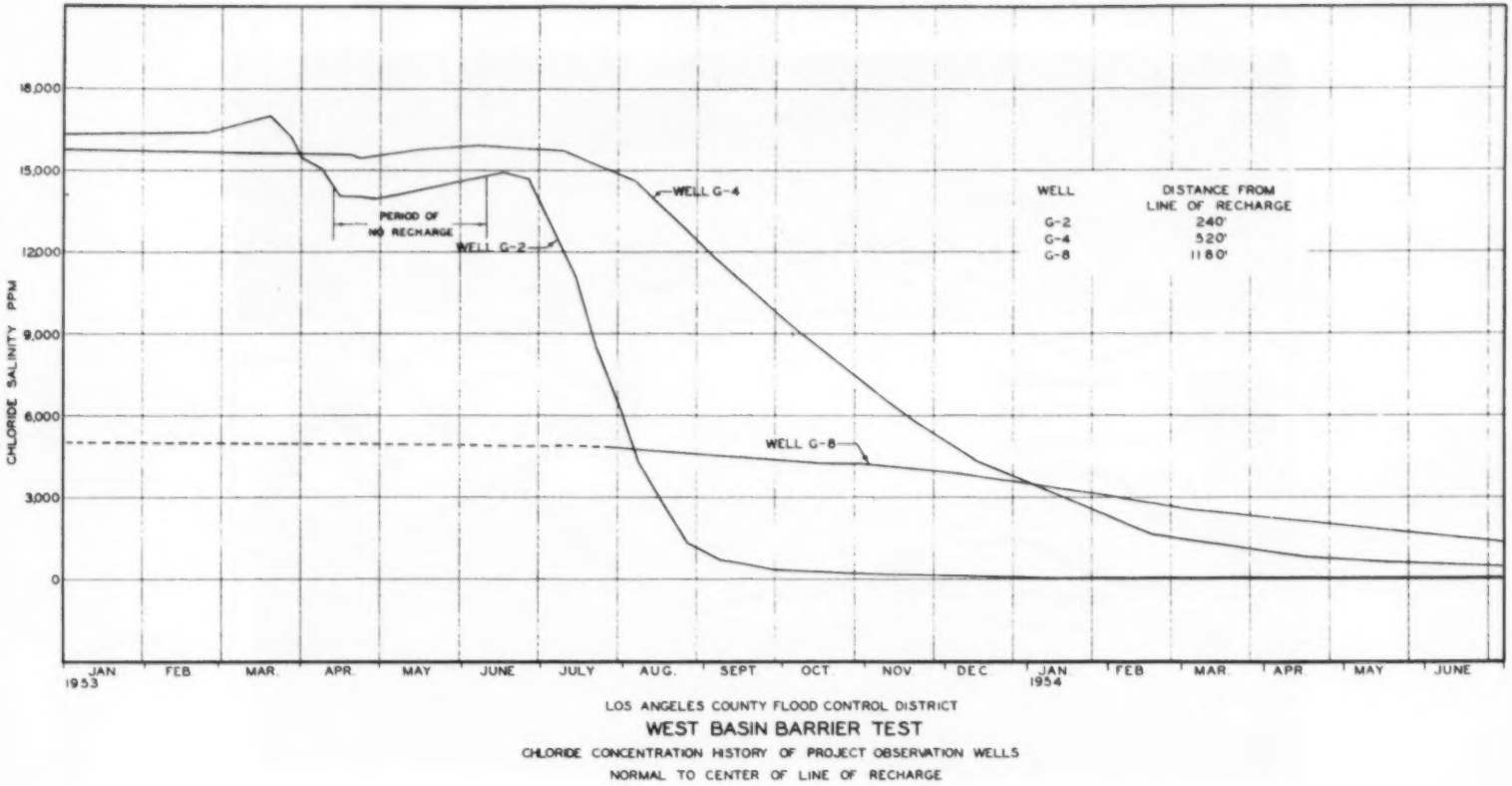

Fig. 7. Passage at Test Wells of "Saline Wave".

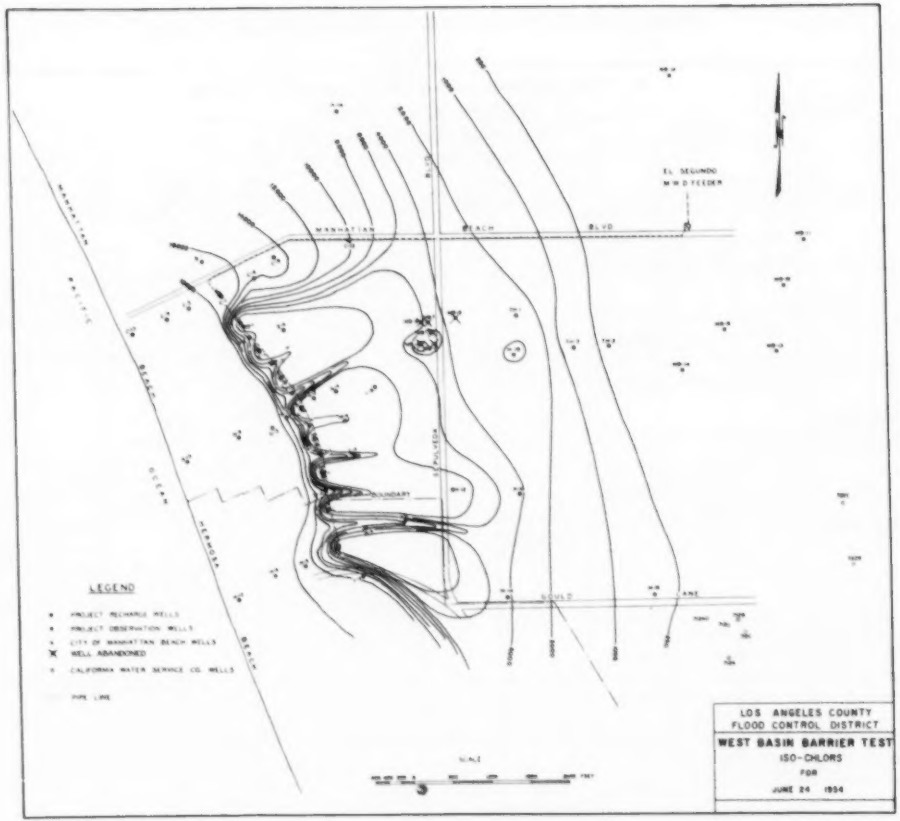

Fig. 8. Iso-Chlor Lines After Sixteen Months of Recharge.

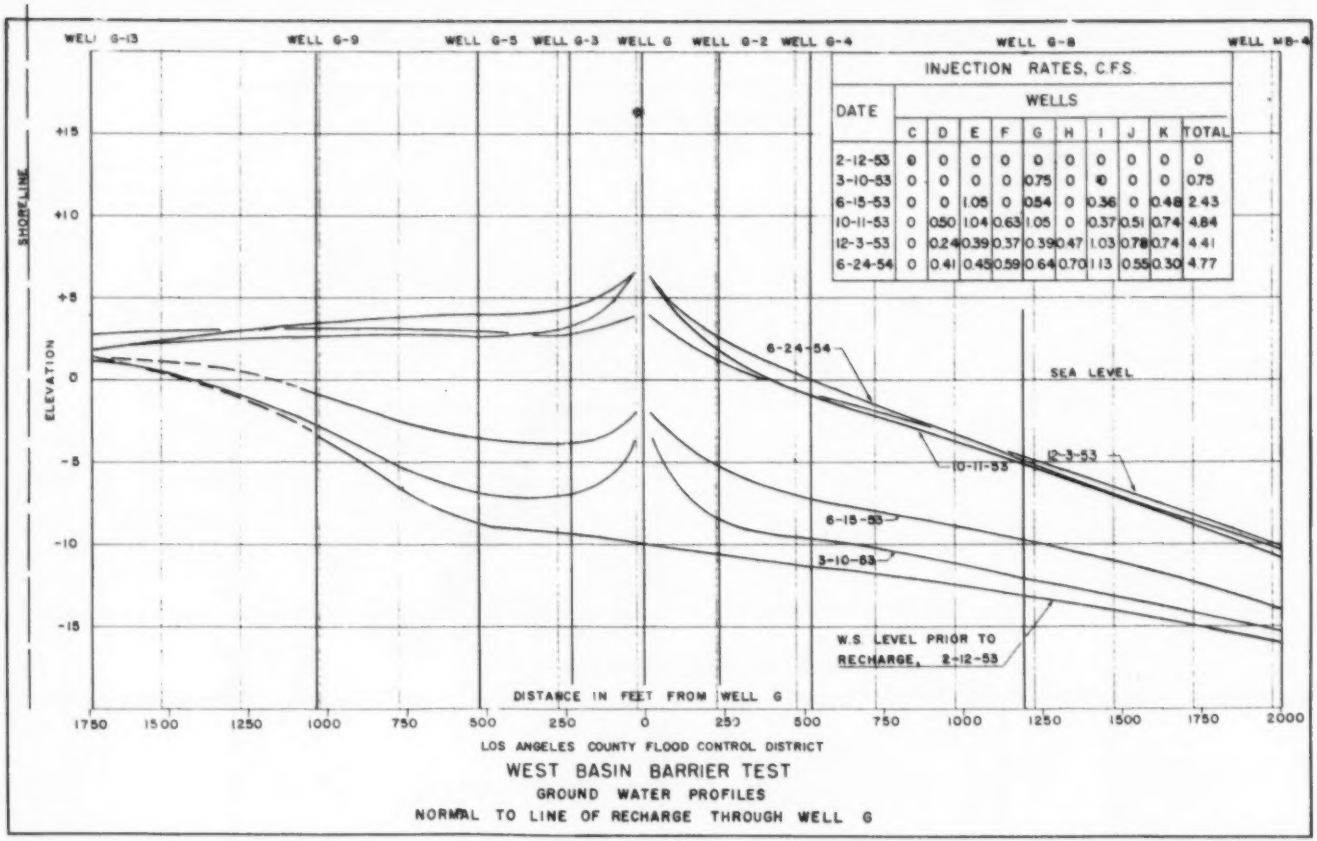
WELL G-13
WELL G-9
WELL G-5
WELL G-3
WELL G
WELL G-2
WELL G-4
WELL G-8
WELL MB-4
SHORE LINE
ELEVATION
+15
+10
+5
0
-5
-10
-15
INJECTION RATES, C.F.S.
DATE
WELLS
C D E F G H I J K TOTAL
2-12-53 0 0 0 0 0 0 0 0 0 0
3-10-53 0 0 0 0 0.75 0 0 0 0 0.75
6-15-53 0 0 1.05 0 0.54 0 0.36 0 0.48 2.43
10-11-53 0 0.50 1.04 0.63 1.05 0 0.37 0.51 0.74 4.84
12-3-53 0 0.24 0.39 0.37 0.39 0.47 1.03 0.78 0.74 4.41
6-24-54 0 0.41 0.45 0.59 0.64 0.70 1.13 0.55 0.30 4.77
6-24-54
SEA LEVEL
10-11-53
12-3-53
6-15-53
3-10-53
W.S. LEVEL PRIOR TO RECHARGE, 2-12-53
DISTANCE IN FEET FROM WELL G
1750 1500 1250 1000 750 500 250 0 250 500 750 1000 1250 1500 1750 2000
LOS ANGELES COUNTY FLOOD CONTROL DISTRICT
WEST BASIN BARRIER TEST
GROUND WATER PROFILES
NORMAL TO LINE OF RECHARGE THROUGH WELL G

Fig. 9. Cross Section of Barrier at Various Stages.

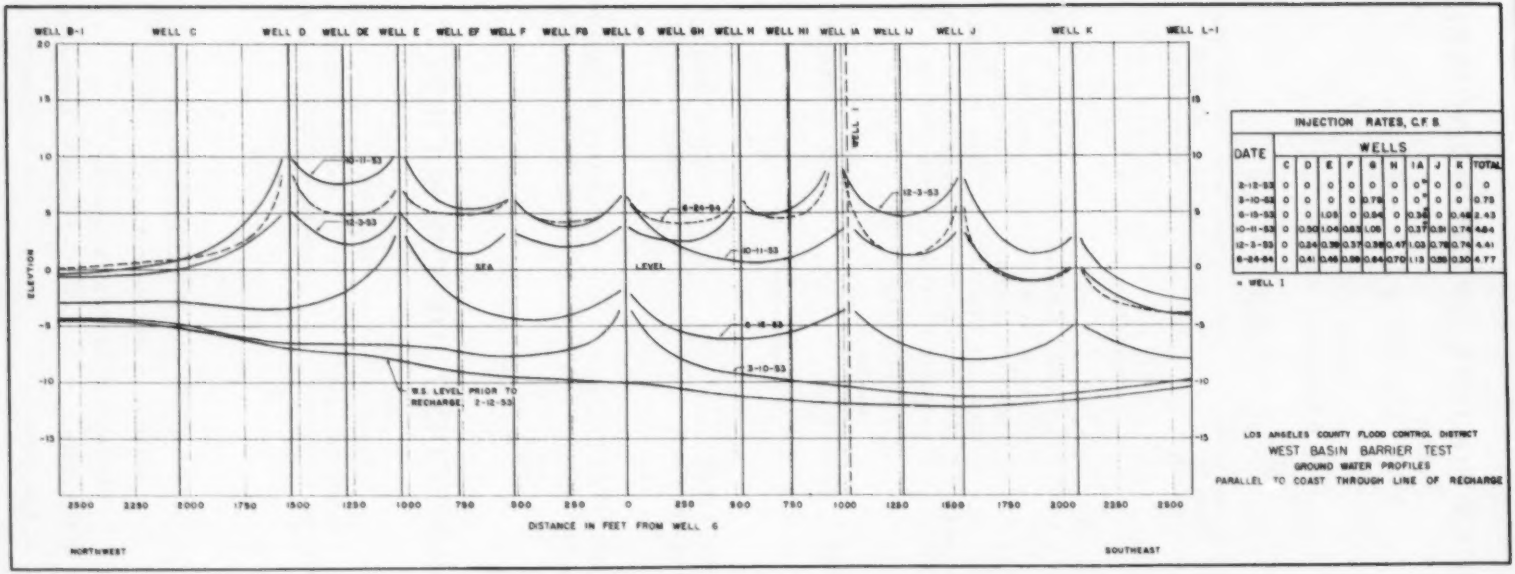

Fig. 10. Profile of Barrier at Various Stages.

AMERICAN SOCIETY OF CIVIL ENGINEERS

OFFICERS FOR 1955

PRESIDENT

WILLIAM ROY GLIDDEN

VICE-PRESIDENTS

Term expires October, 1955:
ENOCH R. NEEDLES
MASON G. LOCKWOOD

Term expires October, 1956:
FRANK L. WEAVER
LOUIS R. HOWSON

DIRECTORS

Term expires October, 1955:
CHARLES B. MOLINEAUX
MERCEL J. SHELTON
A. A. K. BOOTH
CARL G. PAULSEN
LLOYD D. KNAPP
GLENN W. HOLCOMB
FRANCIS M. DAWSON

Term expires October, 1956:
WILLIAM S. LaLONDE, JR.
OLIVER W. HARTWELL
THOMAS C. SHEDD
SAMUEL B. MORRIS
ERNEST W. CARLTON
RAYMOND F. DAWSON

Term expires October, 1957:
JEWELL M. GARRELTS
FREDERICK H. PAULSON
GEORGE S. RICHARDSON
DON M. CORBETT
GRAHAM P. WILLOUGHBY
LAWRENCE A. ELSENER

PAST-PRESIDENTS

Members of the Board

WALTER L. HUBER
DANIEL V. TERRELL

EXECUTIVE SECRETARY
WILLIAM H. WISELY

TREASURER
CHARLES E. TROUT

ASSISTANT SECRETARY
E. L. CHANDLER

ASSISTANT TREASURER
CARLTON S. PROCTOR

PROCEEDINGS OF THE SOCIETY

HAROLD T. LARSEN
Manager of Technical Publications

DEFOREST A. MATTESON, JR.
Editor of Technical Publications

PAUL A. PARISI
Assoc. Editor of Technical Publications

COMMITTEE ON PUBLICATIONS

SAMUEL B. MORRIS, *Chairman*

JEWELL M. GARRELTS, *Vice-Chairman*

GLENN W. HOLCOMB
OLIVER W. HARTWELL
ERNEST W. CARLTON
DON M. CORBETT